GPI: Modeling of AO-corrected coronagraphs

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With slides courtesy of Bruce Macintosh and Christian Marois for the GPI team

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Talk outline

• Science goals and the design of GPI
• How do we estimate performance?
• AO-centric simulation
• Fresnel/Talbot simulations
• The CAL system
• The IFS and the data pipeline
GPI is a science experiment

- Our science team recently was allocated 890 hours for a three-year survey for 600 target stars.

- How do planets form and evolve? (core accretion vs. disk instability)
- What are planetary atmospheres like?
- How do planets migrate? What is their dynamical evolution?

Images from Robert Hurt; NASA Spitzer
GPI has 4 essential tasks and units

- Remove distortions caused by atmospheric turbulence
- Suppress diffraction from the star that obscures the planet
- Use multi-wavelength to aid detection and provide information about the planet
- Fix quasi-static errors that limit sensitivity
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Adaptive Optics

Coronagraph
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Adaptive Optics

Imaging Spectrograph

Coronagraph
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GPI is designed for high-contrast imaging

• Compared to current general purpose AO, GPI has:
  • 10 times the actuator density per area (18 cm spacing instead of 56-60 cm)
  • < 5 nm uncalibrated non-common path error
  • a spatially filtered wavefront sensor to produce a “dark hole”

• Compared to other “extreme” AO systems (Sphere, PALM-3K), GPI has:
  • a MEMS deformable mirror
  • Fourier-transform-based, computationally efficient wavefront reconstruction and self-optimizing control
APLC improves Lyot design

• Apodization allows more efficient destructive interference, providing better cancellation in Lyot plane
• Better throughput and angular resolution
• Built by AMNH (PI: Oppenheimer)

Thanks to R. Soummer for the figure.
APLC improves Lyot design

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Cal system measures quasi-static errors

- Calibration system coupled with APLC
- LOWFS uses light from reference arm for low-order modes
- HOWFS is white-light, phase-shiting interferometer using reference and science light
- Built by JPL (PI: Wallace)
Dedicated hyperspectral imager

- Lenslet-based Integral Field Spectrograph
- $R = 34$ to $80$ from Y to K
- 2.8” x 2.8” FoV
- 0.014” per pixel
- Built by UCLA (PI: Larkin) with U. Montreal and Immervision

Optics test images courtesy of U. Montreal; IFS photo courtesy of UCLA
- Initial performance specs set with analytic error budget in contrast
- Requirements refined through simulations as design progressed
- Req. 1: static and atmospheric speckle noise equal in a 1-hour exposure
- Req. 2: suppress speckle noise to photon noise level through multi-wavelength imaging
The AO simulator is very detailed

- Uses Fourier optics, in particular Fraunhofer propagation
- Multiple layer, frozen-flow, Kolmogorov atmosphere
- LSI Woofer-Tweeter mirrors, with some non-linearities (e.g. saturation) incorporated
- All AO control algorithms fully implemented and data-driven
- Spatial filter simulated with Fourier optics over WFS light
- Quadcell Shack-Hartmann using Fourier optics and CCD characteristics
- Fundamental AO relay misalignments (e.g. centering)
- Individual modules were fully validated against analytic or semi-analytic results
Algorithms and performance predictions

• Simulation designed to give thorough testing to new AO technologies and algorithms for GPI
• Incorporates APLC to give estimated PSFs for short exposures

H-band APLC intensity

3e-7 3e-4

[for comparison] Uniform modal gains
[baseline] Optimized modal gains
[goal] Predictive control

GPI CDR results
PSD approach to AO performance

• In addition to individual module validations, we wanted an over-all “sanity check”
• AO simulator takes too long; need something faster for science team

• Approximate the PSF with the PSD term of the “PSF expansion”
• Several treatments exist (Ellerbroek; Guyon; Jolissaint)

Validated GPI monte carlo simulator

- Made additions to model the unique features of GPI AO
- Found very good agreement between short-exposure monte carlo PSFs and PSD approach
- PSD code is used by science team
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PSD code is used by science team

I=6, five-layer 14.5 cm r0 atmosphere, 2 kHz, Optimized-gain controller, 700-900 nm WFS, APLC at 1.625 microns, 5 second exposure

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Our AO simulator can’t do everything

- No Fresnel propagation between phase screens in atmosphere (but scintillation negligible)
- Idealized pupil-plane/focal-plane model of AO relay: no out-of-plane optics!
- Simulation is achromatic
- Individual runs are limited by phase screen size to ~ 4 seconds

- How to consider these other terms?
- Will not be done in the AO monte carlo code
Talbot imaging: phase-induced ampl. errors

- From Fresnel propagation

- Valid for:
  - Infinite wavefronts
  - Collimated beam
  - Small aberrations
  - Easy to implement

- A pure phase is oscillating between pure phase and a pure ampl. aberration over a length equal to:

\[ \tau_L = \frac{2\Lambda^2}{\lambda} \]

where \( \Lambda \) is the aberration spatial period.
GPI raw static contrast from each plane

Gray APLC at opt wavelength with Talbot propagated static aberrations (no SSDI & 2h ADI)
Perfect phase correction inside dark hole
M3 at pupil

5σ Detection Limit (Δ mag)
Angular Separation (λ/D)
Conclusions

Limiting magnitude (for AO): I-mag < 9-10

Spectral bands: Y, J, H, K

Spectral resolution: IFS with R~45 at H (~same at J and K-band)

Broadband polarimetric mode

FOV: 2.9” x 2.9”

Inner working angle: 2.8 lambda/D radius

Dark hole size: 21 x 21 lambda/D

Contrast: up to 10^-7 from PSF peak intensity

First light: December 2010

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Tolerance Analysis

- CAL Residual less than ~3nm RMS MSF.
- Entrance window needs to be clean.
- Spider Lyot mask os no more than ~3%.
- Reach 10^7 photon limited contrast at a few I/D in 1h integration time (goal) with SSDI & ADI.

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To be Continued...

End-2-End Fresnel Prog. II

SPIE 2010

Angry Photons Strike Back

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How do we deal with AO-Cal interaction?

• GPI’s calibration system will help correct static and quasi-static errors on the time scales of minutes
• Its measurements are used by the AO system

• Can’t just simulate the Cal system and run the AO simulator for a 30-minute run!

• Instead we
  • estimate residual AO error seen by the Cal system
  • use mechanical models to show growth of quasi-static errors through time (e.g. from flexure)
  • use Simulink to model the Cal system’s slow closed-loop as implemented with AO references
Simulation method: AO side

- Store AO telemetry (as for gain optimization and prediction)
- Evaluate residual error power temporal PSDs for
  - specific low-order Fourier modes seen by the LOWFS
  - all the other Fourier modes seen by the HOWFS
- Do this for all magnitudes of interest with OFC
  - assume H-I = 0 for obtaining AO performance

Residual error, full simulation and PSD model

In-band RMS wavefront error (nm)

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Defining the time-varying NCP errors

- Thermal flexure, gravity loading and atmospheric dispersion analysis to determine beam motion
- Convert into wavefront error given optics involved

<table>
<thead>
<tr>
<th>NCP source</th>
<th>Max WFE (nm)</th>
<th>Max rate (nm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexure</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Atm disp beam walk</td>
<td>2.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

GPI CDR results

Pupil centering on PPM (port 1), 15 deg/hr motion

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Simulation method: Calibration side

- Construct Simulink model (and Laplace model) based on flow diagram shown earlier
- Use TT/LOWFS/HOWFS noise variances per exposure as determined by JPL
  - Assume slower updates achieved by averaging fast measurements [temp.white]
  - Assume CAL returns unbiased, gain = 1 measurement of NCP
- Make deterministic NCP signal from twice GPI expected error
- Use temporal PSDs to generate AO residual signals
  - HOWFS/LOWFS: AO residual from end-to-end simulation
  - TT: Gemini South P2/OIWFS median profile
- Find Calibration update rate that meets tracking noise requirement given AO residual and Calibration noise
- Run Simulink to verify performance
Convergence on initial NCPE

$I=5$, 1-minute updates, $g=0.5$, no noise

Tracking slowly varying NCP errors, $I=5$

Convergence on initial NCPE

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tracking noise in steady state

\( I=5, \, 1\text{-minute updates, } g=0.5 \)

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**Graph:**

- Title: Tracking slowly varying NCP errors, \( I=5 \)
- Y-axis: NCPE and correction (nm)
- X-axis: Time (minutes)
- Graph shows the convergence to 1 nm over time.

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**Text:**

- GPI CDR results
- Friday, February 17, 2012
Convergence on initial NCPE

$I=8$, 2-minute updates, $g=0.32$, no noise

Tracking slowly varying NCP errors, $I=8$

Convergence on initial NCPE

GPI CDR results

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Tracking noise in steady state

$l=8$, 2-minute updates, $g=0.32$

Tracking slowly varying NCP errors, $l=8$

Convergence to 1 nm

GPI CDR results

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IFS simulation step 1: detector images

• Part 1: light through the IFS
  • setup up the observation: star [planet] parameters like magnitude, spectrum, observation length, field rotation, etc.
  • uses PSFs generated by AO simulation for both star and planet
  • several noise sources (detector noise, atmospheric transmission, sky background)

Figure from Maire, “Data reduction pipeline for the Gemini Planet Imager”, SPIE 7735
IFS simulation step 2: build data cube

- Part 2: data pipeline to construct data cubes from IFS reads
  - need to calibrate to get wavelength solution
  - from each IFS image, integrate over small regions; assign flux to a wavelength
  - interpolate onto common wavelength vector across all mini-spectra

- This is non-trivial!

Figure from Maire, “Data reduction pipeline for the Gemini Planet Imager”, SPIE 7735
Putting it all together

• For GPI performance, we have used a wide range of simulations and techniques to evaluate instrument performance

• For this workshop, I have linked several of these to make the data challenges.

• Good luck!

• Questions?